The competing spin liquids and symmetry fractionalization for triangular lattice J1-J2 spin-1/2

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FTPI workshop

Research is supported by NSF (magnetic systems) and DOE (topological matter)

Research team:

Wenjun Hu, ShouShu Gong (frustrated spins)

Wei Zhu (topological matter)

Hu, Gong, Zhu, Sheng, arXiv1504.00654 (SLs competing)

A related work by Z. Zhu and Steve White
arXiv1502.04831 (Z2 SL)

Outline

The intermediate phase for triangular J1-J2 Heisenberg model

J2=(0.08, 0.16)J1 ---- nonmagnetic, spin liquids candidate

Evidence of Chiral spin liquid: long-range chiral correlations in even sector (no pinning or inserting flux), TRS breaking

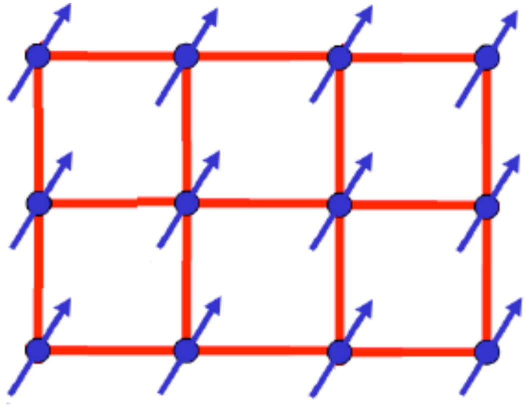
Evidence of Z2 spin liquid: exponential decay chiral correlations in spinon sector (with pinning or inserting 2pi spin flux) ---Z2 sector agrees with Zhu and Steve’s work

Energy near degeneracy; entanglement spectrum, chiral edge spectrum in even sector; Evidence of symmetry fractionalization for “fermionic spinon Sector”

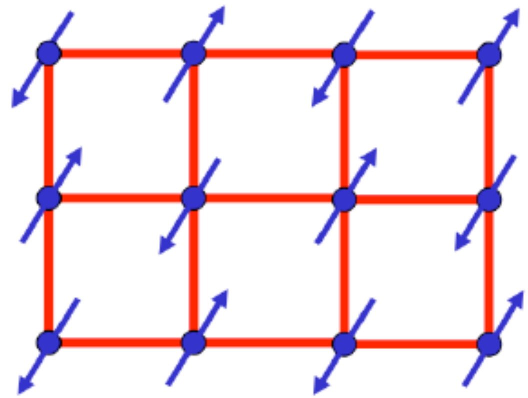
We don’t know which one will win at thermodynamic limit!

Magnetic systems intend to develop orders by breaking symmetry

J<0

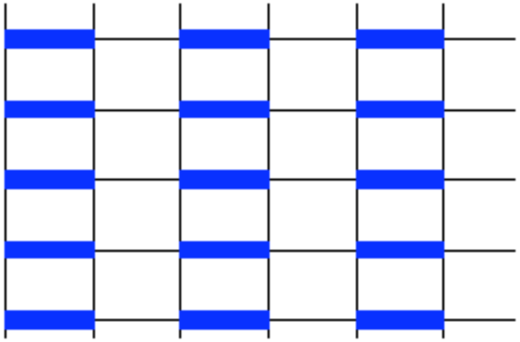


Ferromagnetic order

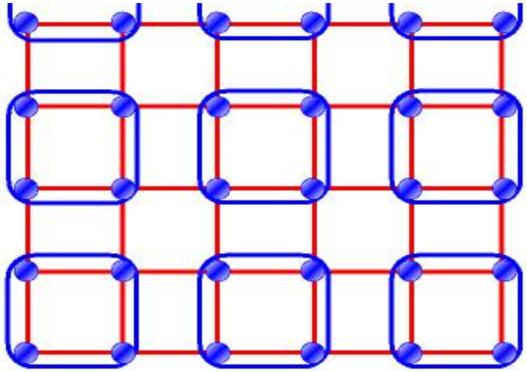


J>0

Antiferromagnetic order with NN J1



Valence Bond Solid (VBS) order

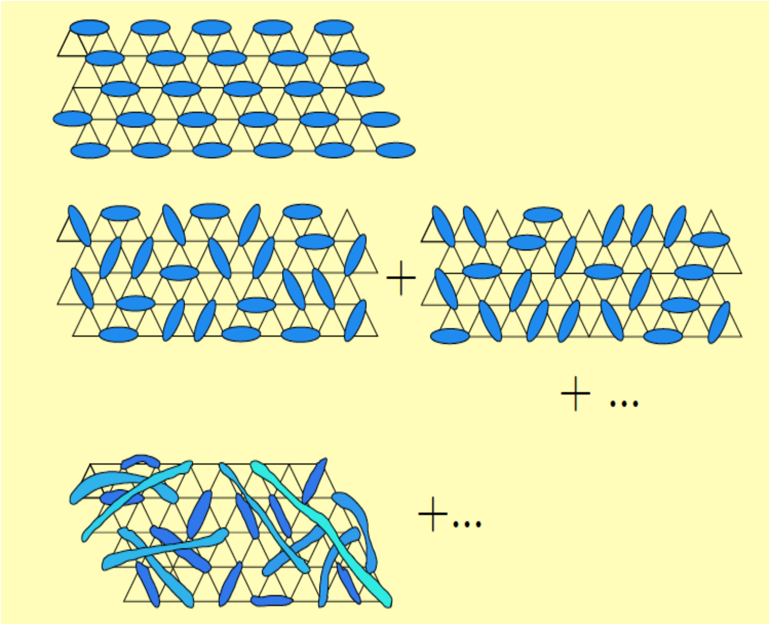


Plaquette VBS (possibly identified in J1-J2 square model)

Spin Liquid (SL) State

A new state of matter with no symmetry broken, with topological order and fractionalized spinons

X. G. Wen (1990, 1991)



Z2 SL in contrived theoretical models
Wen (1990,1991), Kivelson, Rokhsar, Sethna (1987), Senthil, Fisher (2000), Balents, Fisher, Girvin (2002) Moessner and Sondhi, (2001), Senthil, Motrunich (2002) Senthil, Vishwanath, Balents, Sachdev, Fisher (2004) PA Lee (2008), Balents (2010) ....

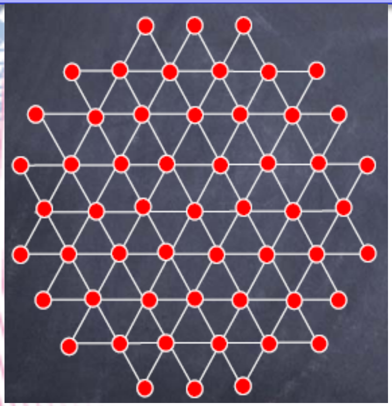
Gapped SL State

Gaps to all spin excitations

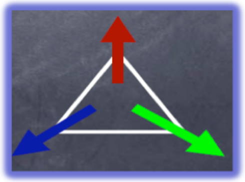
exponential decay correlations

J1-J2-J3 (Ising) kagome, Balents et al and J1 kagome model

Spin liquids in Heisenberg models with increasing frustration



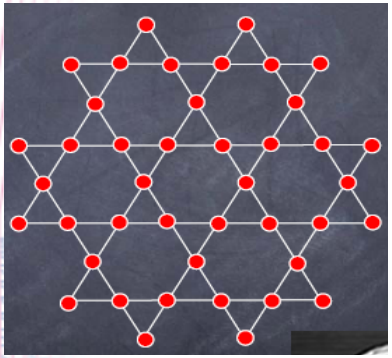
Triangular lattice



Three-sublattice AF order

Resonating valence bond (P. W. Anderson), RVB is a quantum spin liquid (SL)1973, 1989

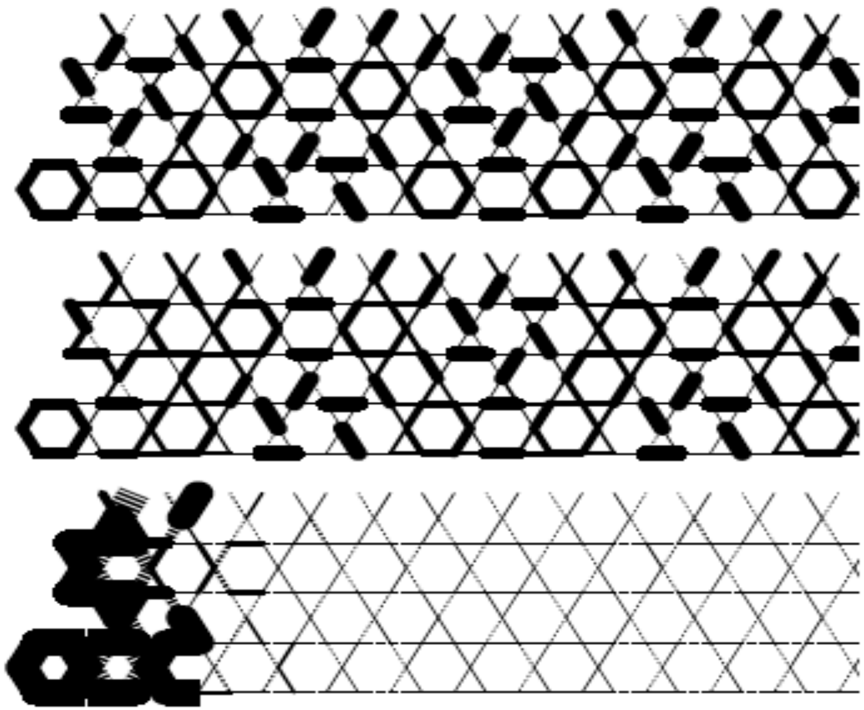
NN Kagome lattice: A primary candidate for Z2 SL



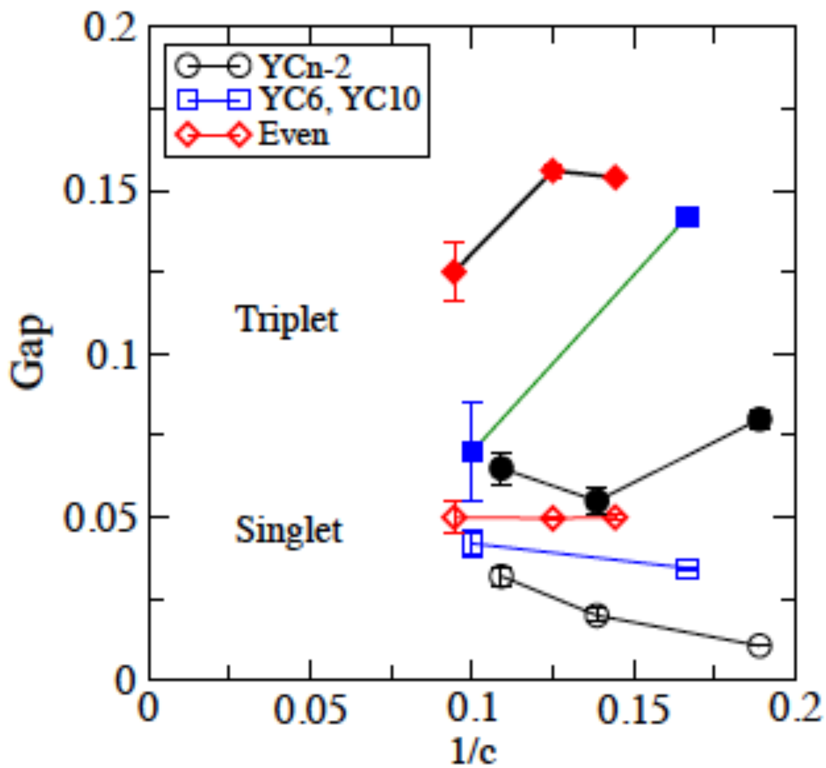
Spin Liquid
H.C. Jiang, Z.Y. Weng, DNS (2008), not converged DMRG for wider systems
Yan, Huse, White, Science (2010)---new milestone: A possible gapped spin liquid

Jiang, Wang, Balents (2012)
Depenbrock et al. (2012).

Main evidence for possible Z2 for J1 kagome spin1/2 (DMRG, Yan et al)



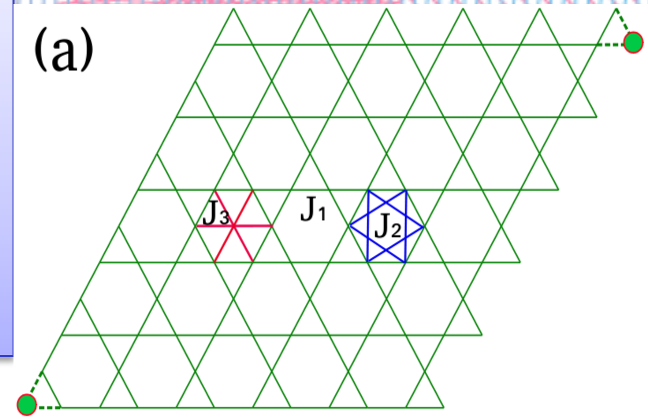
Evolving to uniform SL from VBS on kagome



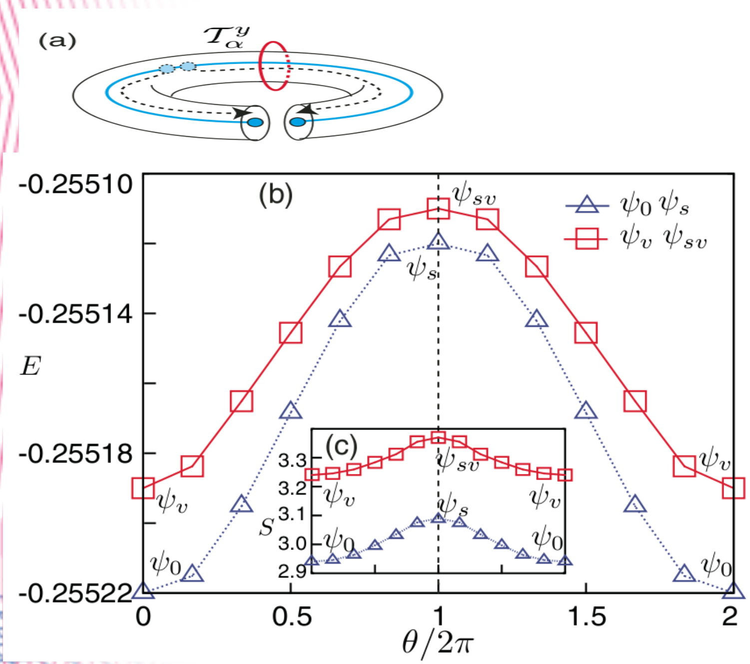
Yan, Huse, White, 2010 found two topological sectors in DMRG; Challenge to find four sectors to fully establish topological nature of the phase

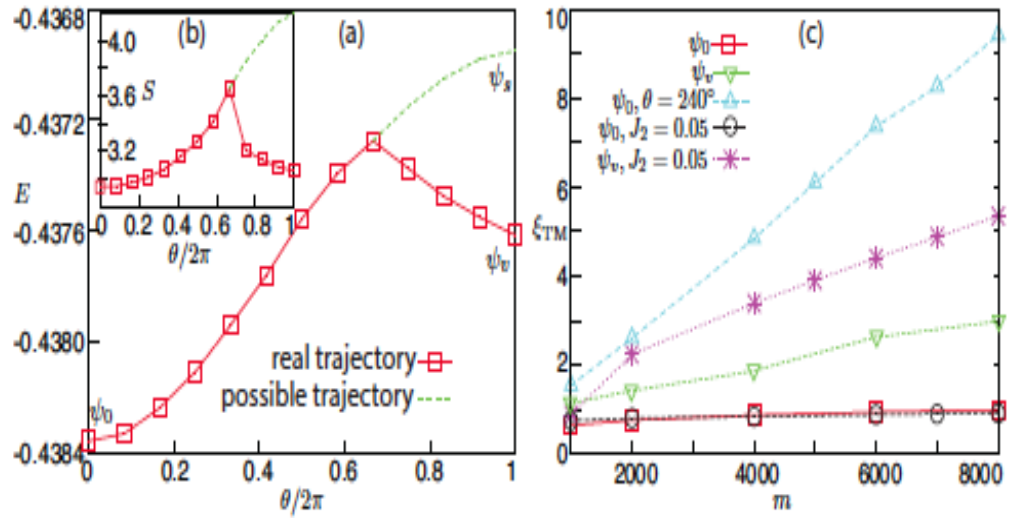
Adiabatic DMRG: by pinning and inserting flux adiabatically on cylinder to access all top. Sectors

Y. He, Sheng, Y. Chen



J1-J2-J3 model with large Jz (or small Jxy1)
He, DNS, Chen PRB(2014)





Inserting flux to get 4 sectors (adiabatic DMRG) did not work for NNK because “vison-like” excitations are gapless; and fractionalized spinon in CSL is still there.

Spin-1/2 KAF: Experimental findings for Herbertsmithite

$ZnCu_3(OH)_6Cl_2$

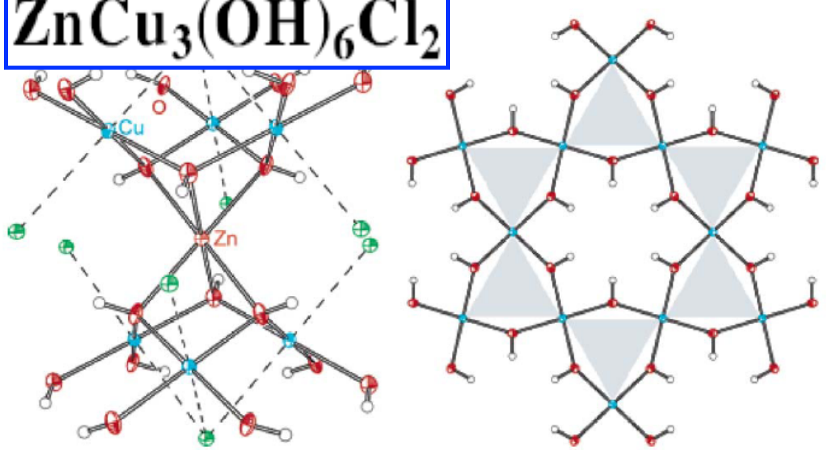
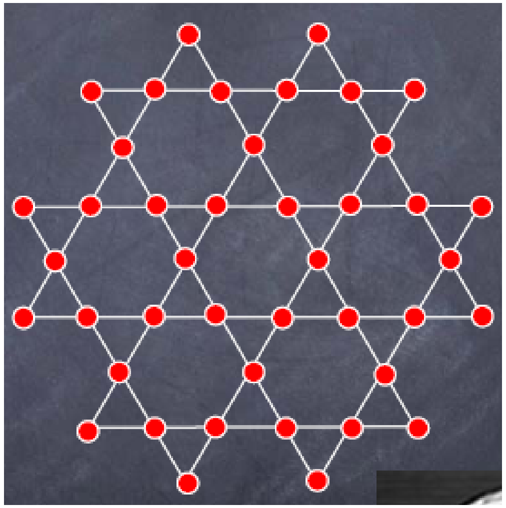


Figure 1. Crystal structure of Zn−paratacamite (**1**), $Zn_{0.33}Cu_{3.67}(OH)_6Cl_2$.



- ✓ No magnetic order down to 50 mK
- ✓ No observable spin gap down to 0.1 meV

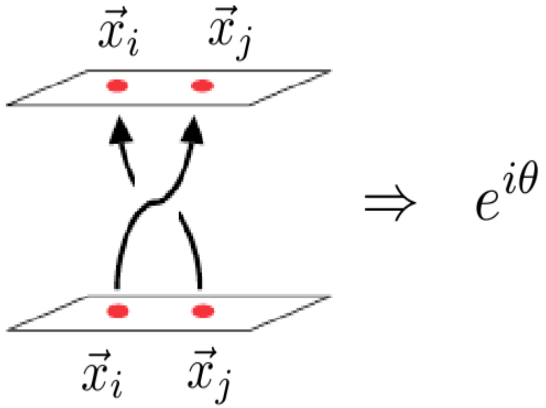
⇨ SL Phase, but different from identified by DMRG

Gapless SL for kagome,
Y. Iqbal et al,arXiv:1209.1858

J. S. Helton et al., Phys. Rev. Lett. 98, 107204 (2007); O. Ofer et al., arXiv:condmat/0610540.
P. Mendels et al., Phys. Rev. Lett. 98, 077204 (2007). A. Olariu et al., Phys. Rev. Lett. 100, 087202 (2008).

Time reversal symmetry (TRS) broken chiral Spin liquid (CSL): a bosonic FQHE state

Kalmeyer and Laughlin 1987
Wen, Wilczek, Zee 1989



anyon quasiparticles obey fractional statistics, chiral ordering, TRS and parity broken spontaneously

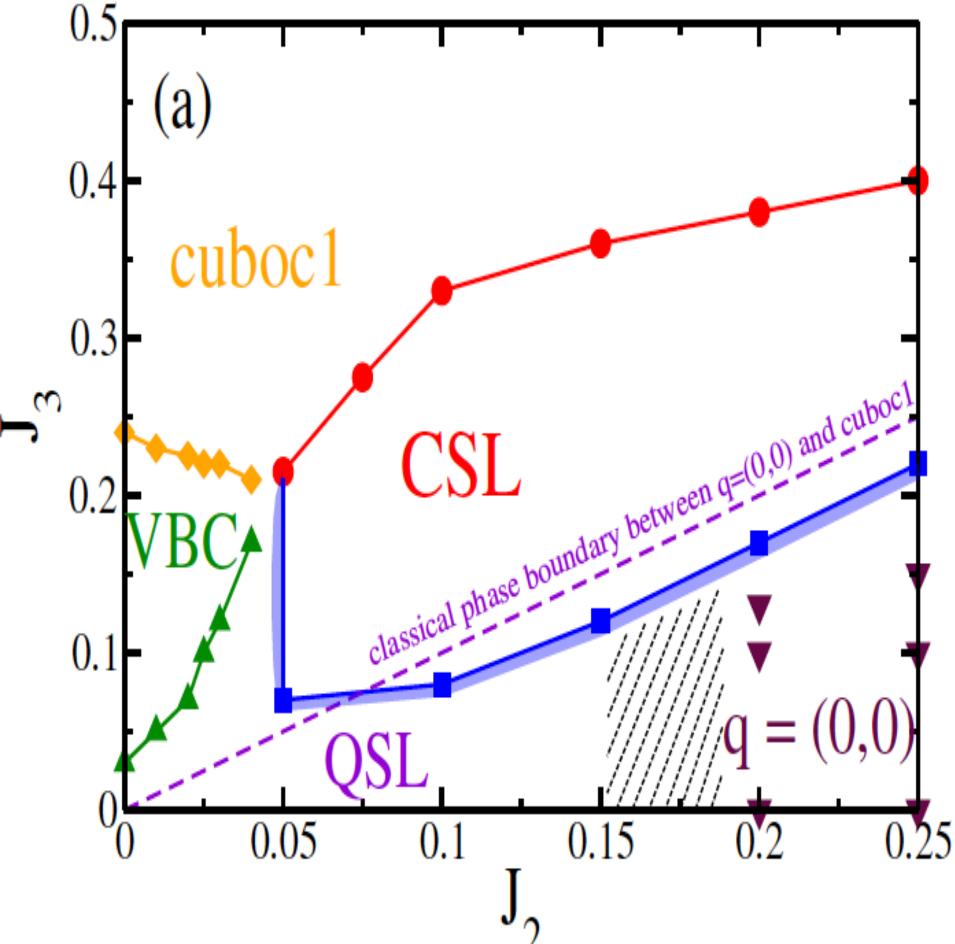
Induce CSL using (S1XS2)*S3 interaction

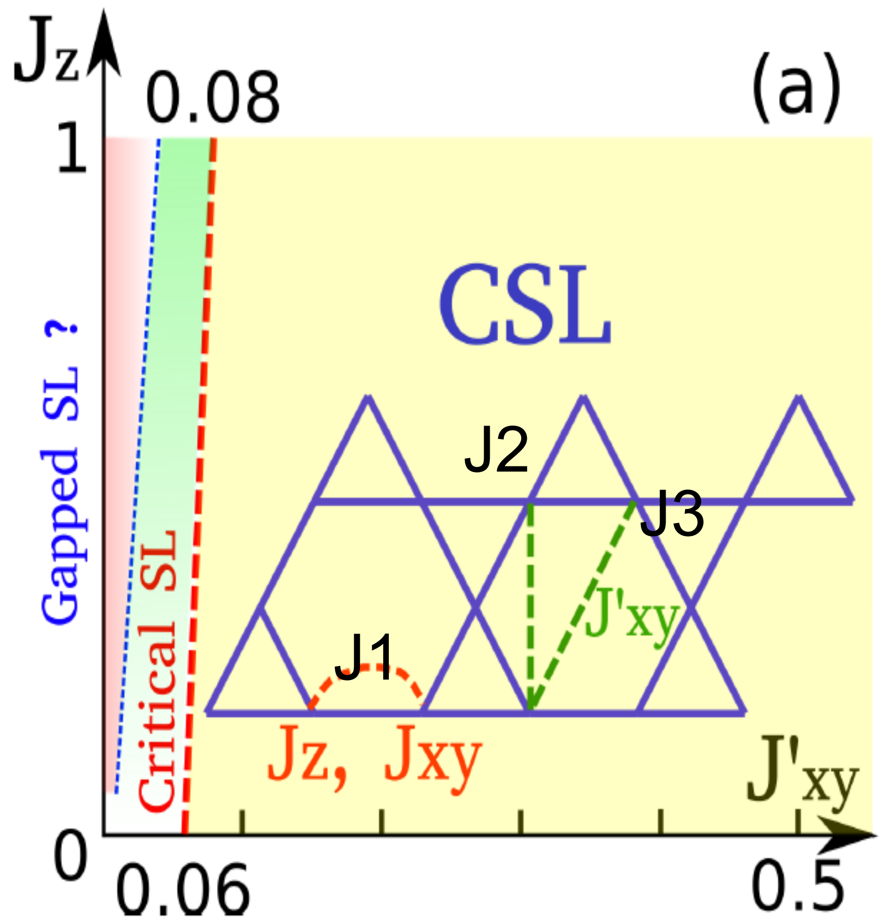
Haldane and Arovas 1995
Chern number to distinguish it from chiral spin state
Yang, Warman and Girvin1993.
Yao and Kivelson: a contrived CSL state (for Kitaev model) 2007

Induce CSL with TRS broken terms
Schroeter et al 2007, Thomale et a. 2009, Nielsen et al. 2012, Bauer et al. 2013-2014 (Mott materials)
Approx. Methods find CSL
Hermele et al (2009), Messio et al. For kagome J1-J2-J3 (2012) Cuboc

robust examples of discovering CSL in kagome spin ½ models

$$H = J_1 \sum_{\langle i,j \rangle} S_i \cdot S_j + J_2 \sum_{\langle\langle i,j \rangle\rangle} S_i \cdot S_j + J_3 \sum_{\langle\langle\langle i,j \rangle\rangle\rangle} S_i \cdot S_j$$



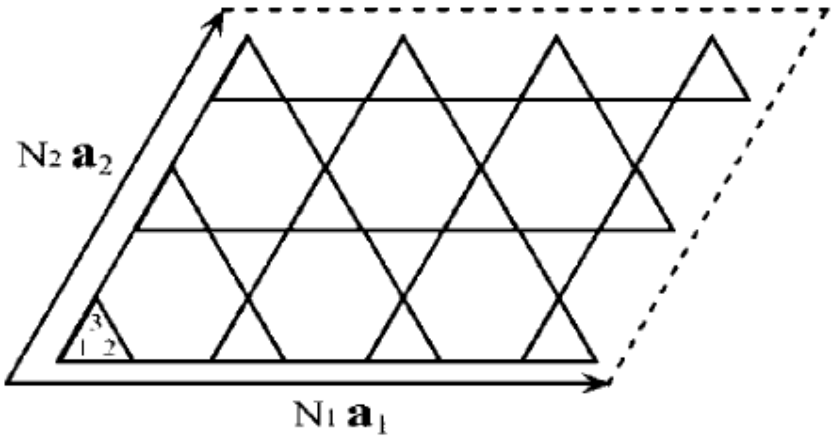


Density matrix renormalization group (DMRG) m=6000--30000 (U1 equivalent) states using SU2

S. R. White 1992

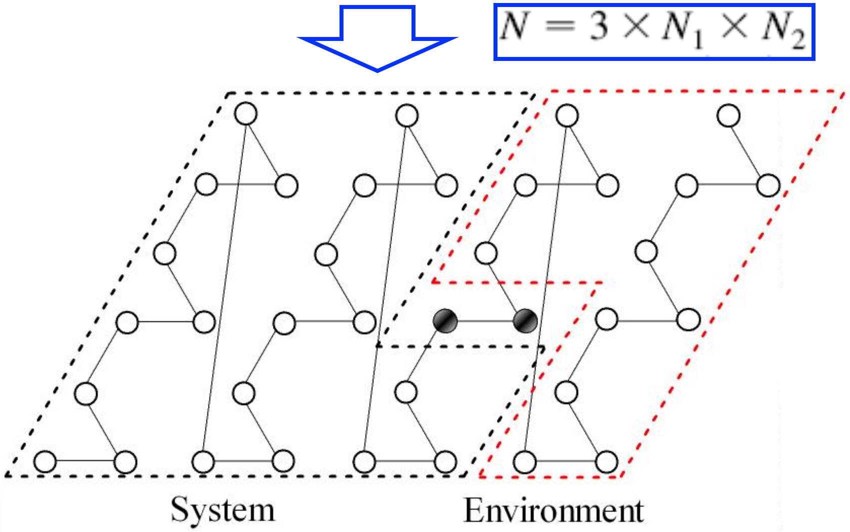
1D DMRG algorithm

Mapping a 2D lattice onto a 1D



Jiang, ZY Weng, DNS(2008)

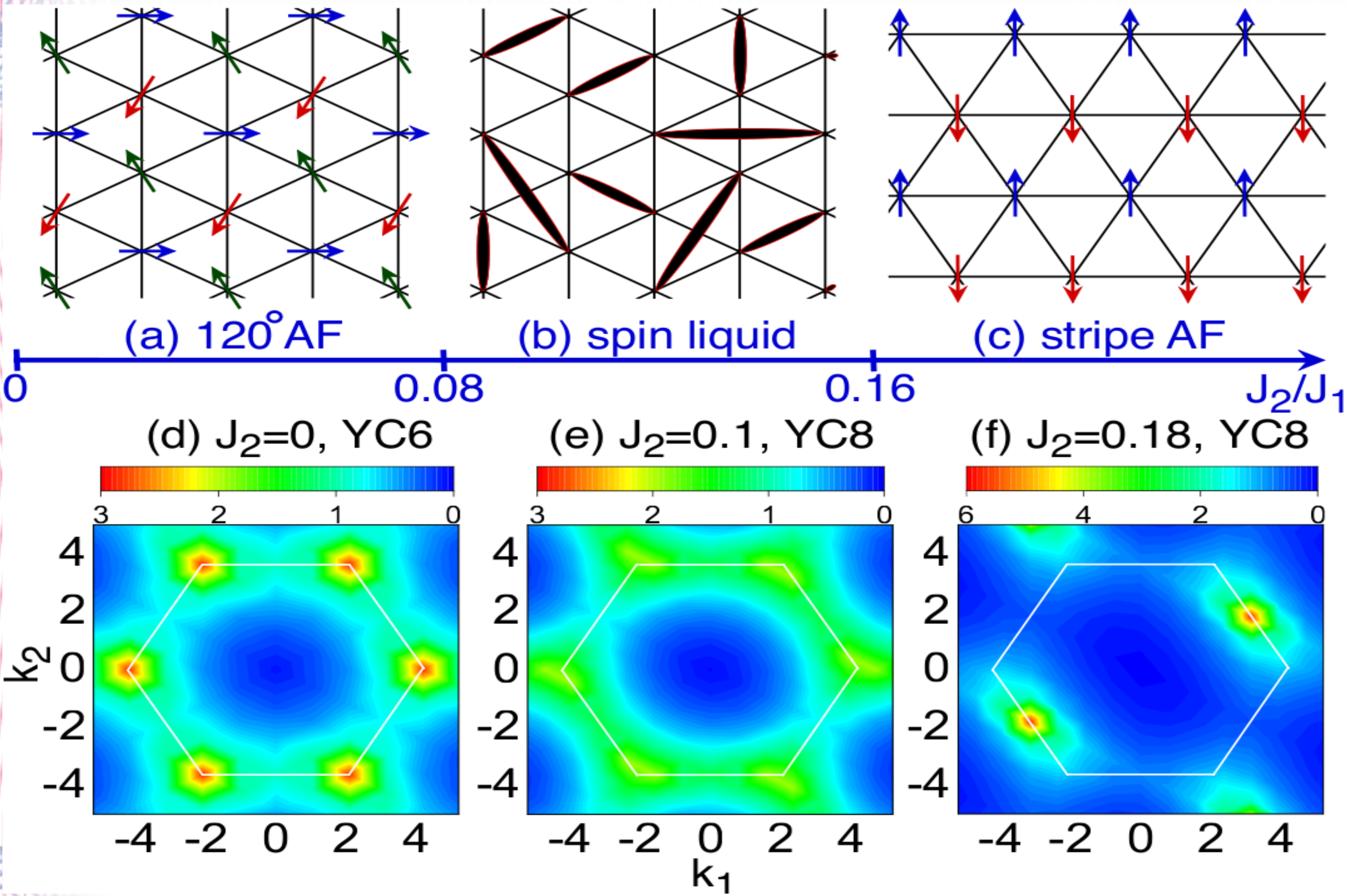
$\boxed{N = 3 \times N_1 \times N_2}$



DMRG with Su2 invariant
up to 30,000 states
Shoushu Gong

Depenbrock et al. 2012

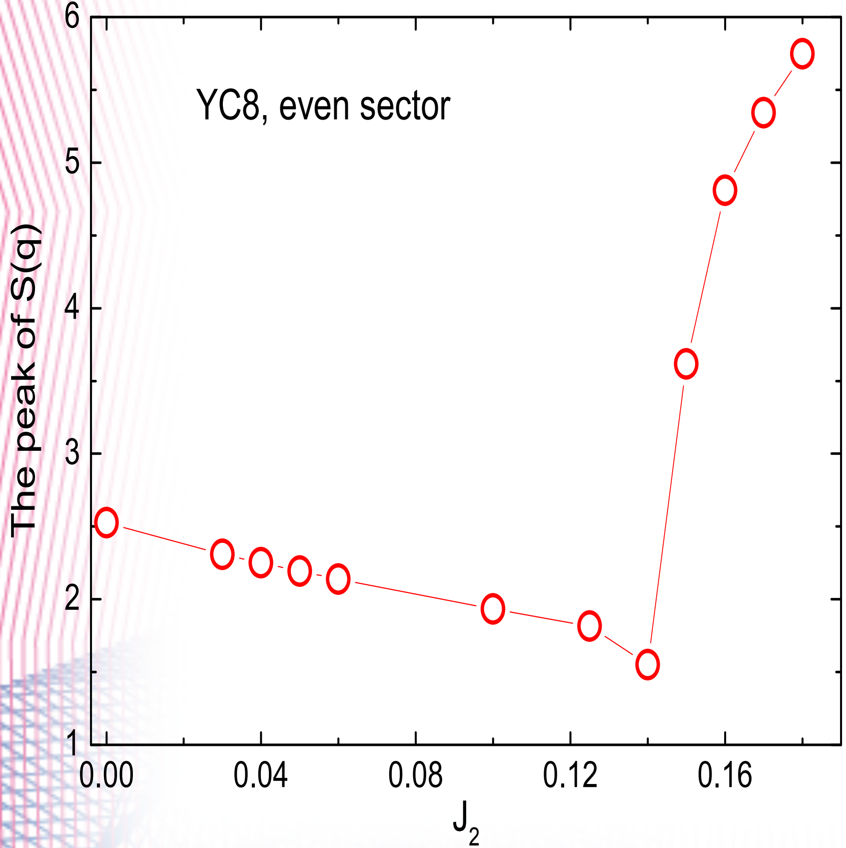
Frustrated triangular lattice spin ½ J1-J2 models



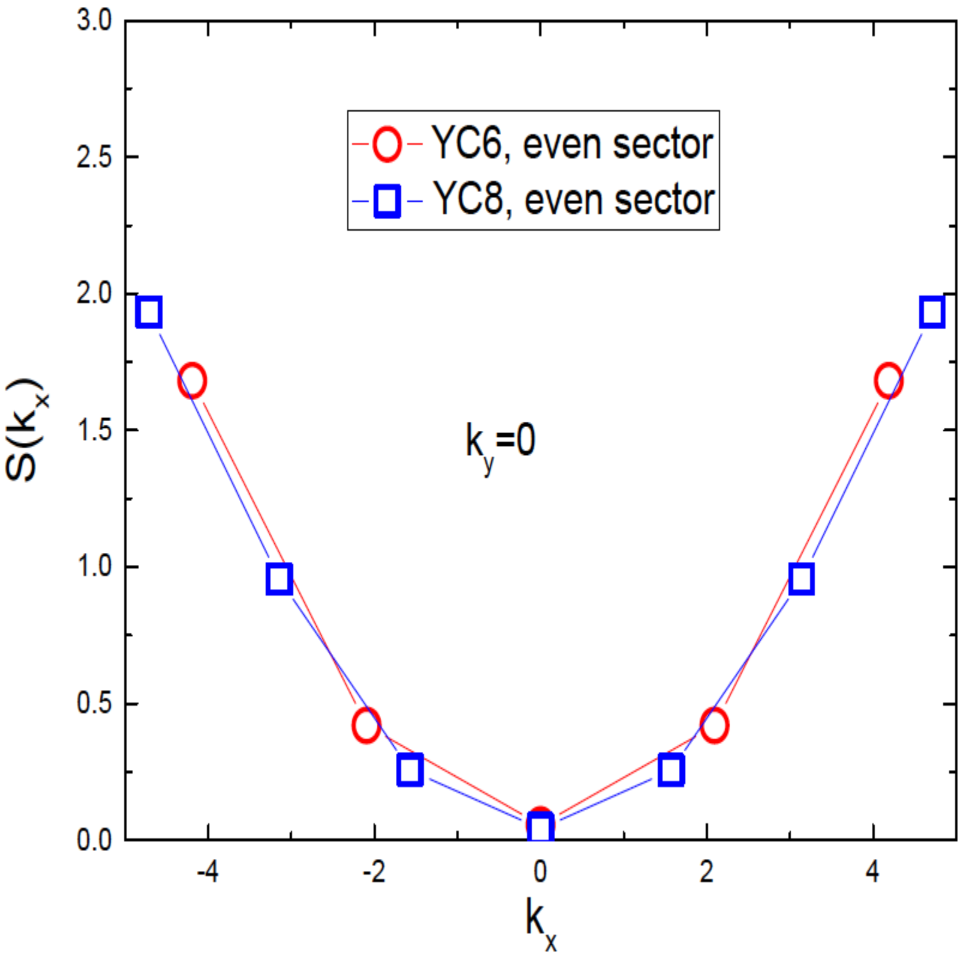
Z. Zhu and S. R. White, arXiv:1502.04831

Spin structure factors

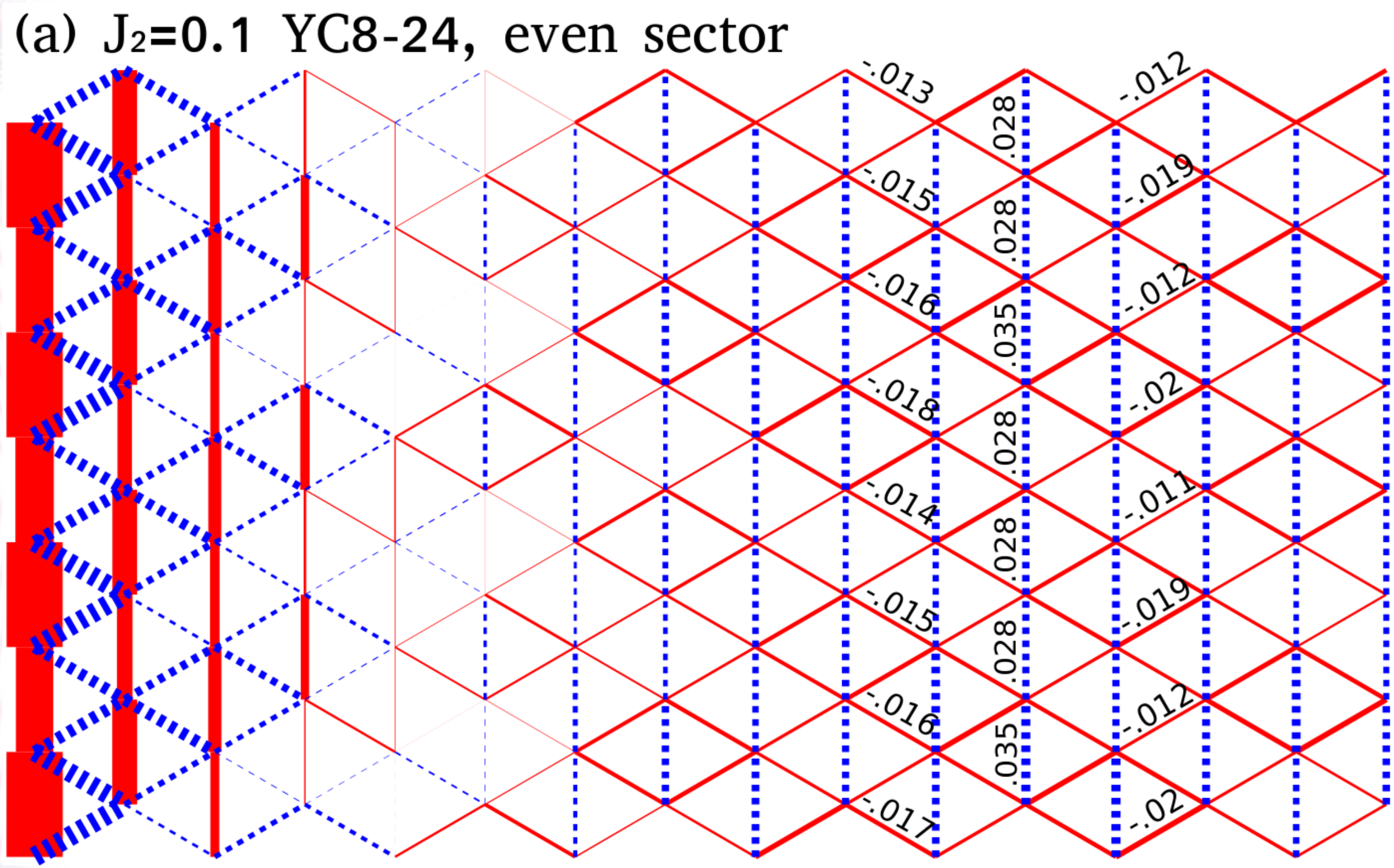
1^{st} order sign of SL to stripe phase



SL with size independent S

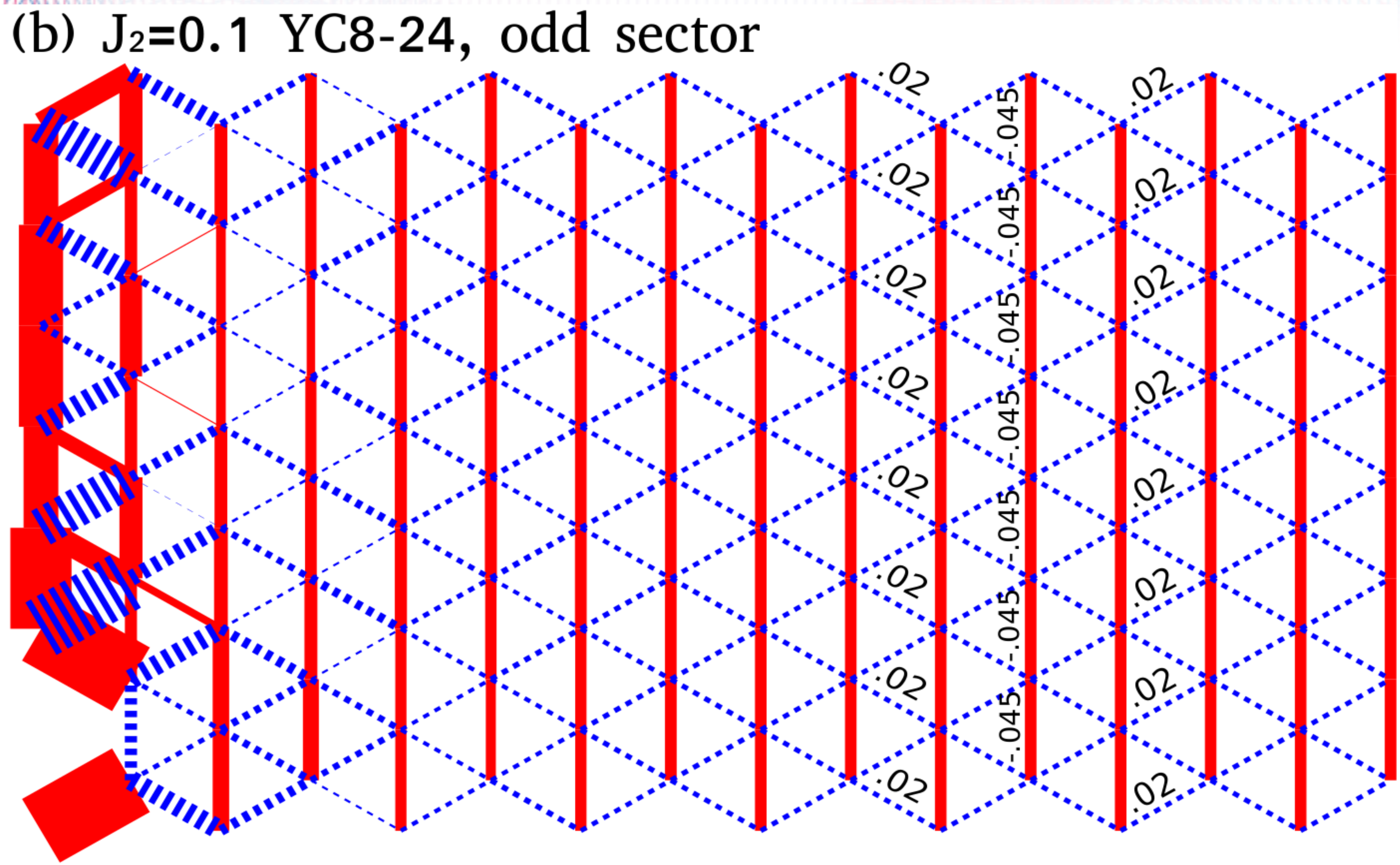


SL phase around J2=0.1, uniform ground state (even sector)



Even sector: short range spin, dimer but long-range chiral correlations

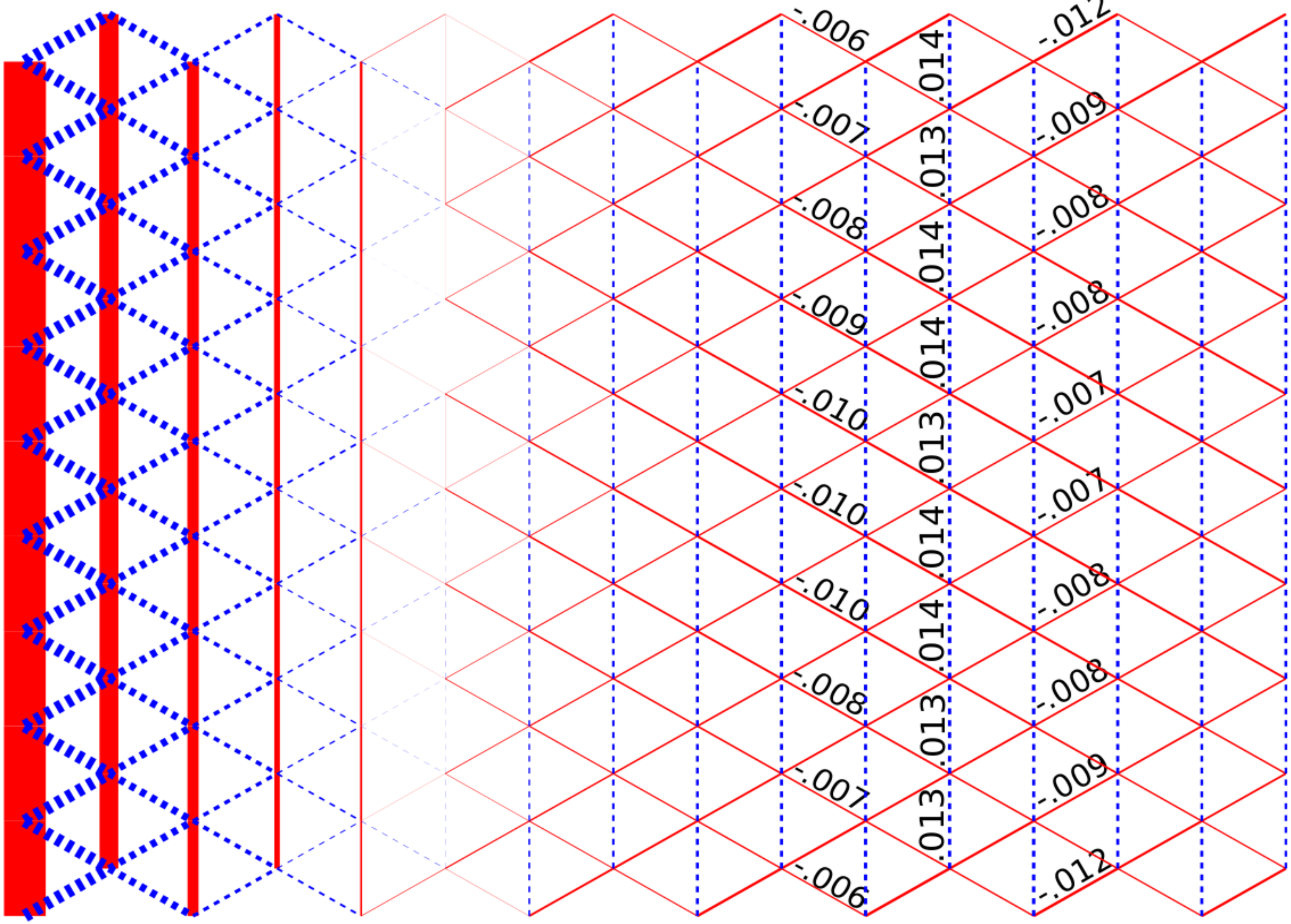
SL phase around J2=0.1, spinon sector, nemetic order?



Pinning, odd sector: short range spin, dimer
Also short-range chiral

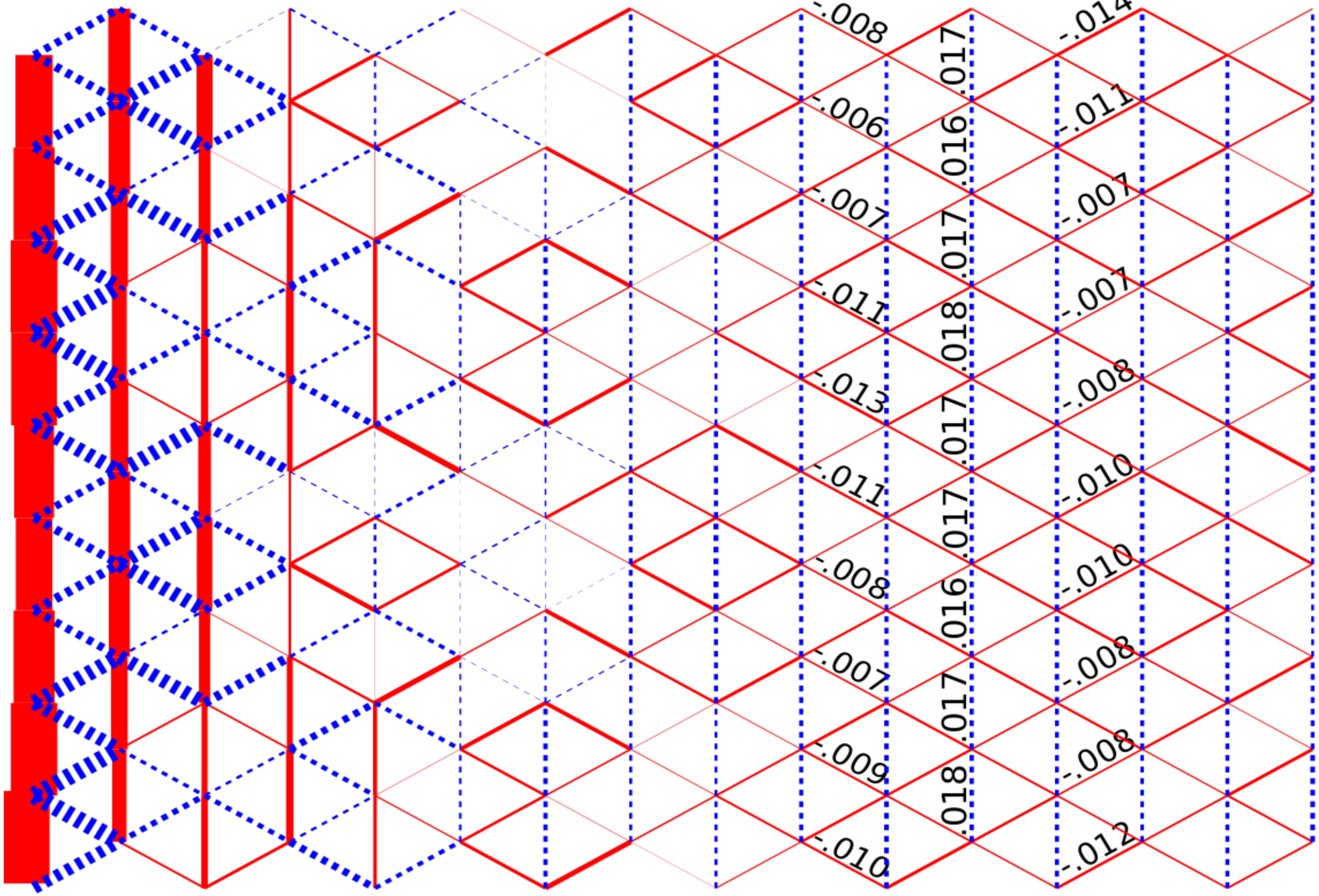
SL phase around J2=0.1, time reversal symmetry is broken: chiral order is strong in even sector

(b) J_2=0.1, YC10-24, $M_{SU(2)}$=4000, complex, E=-122.993



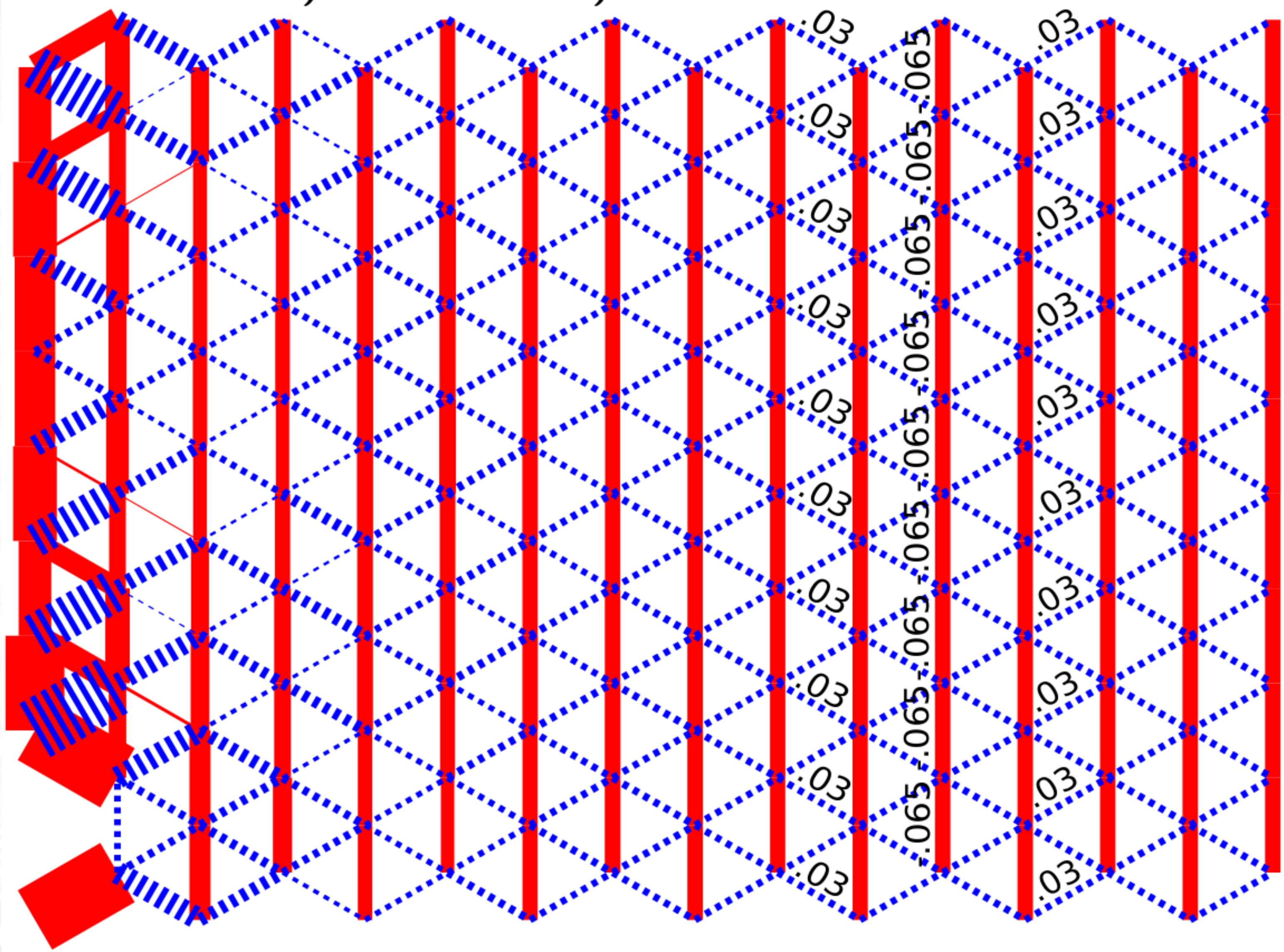
SL phase around J2=0.1, vacuum sector

(a) J_2=0.1, YC10-24, $M_{SU(2)}$=5000, real, E=-123.019

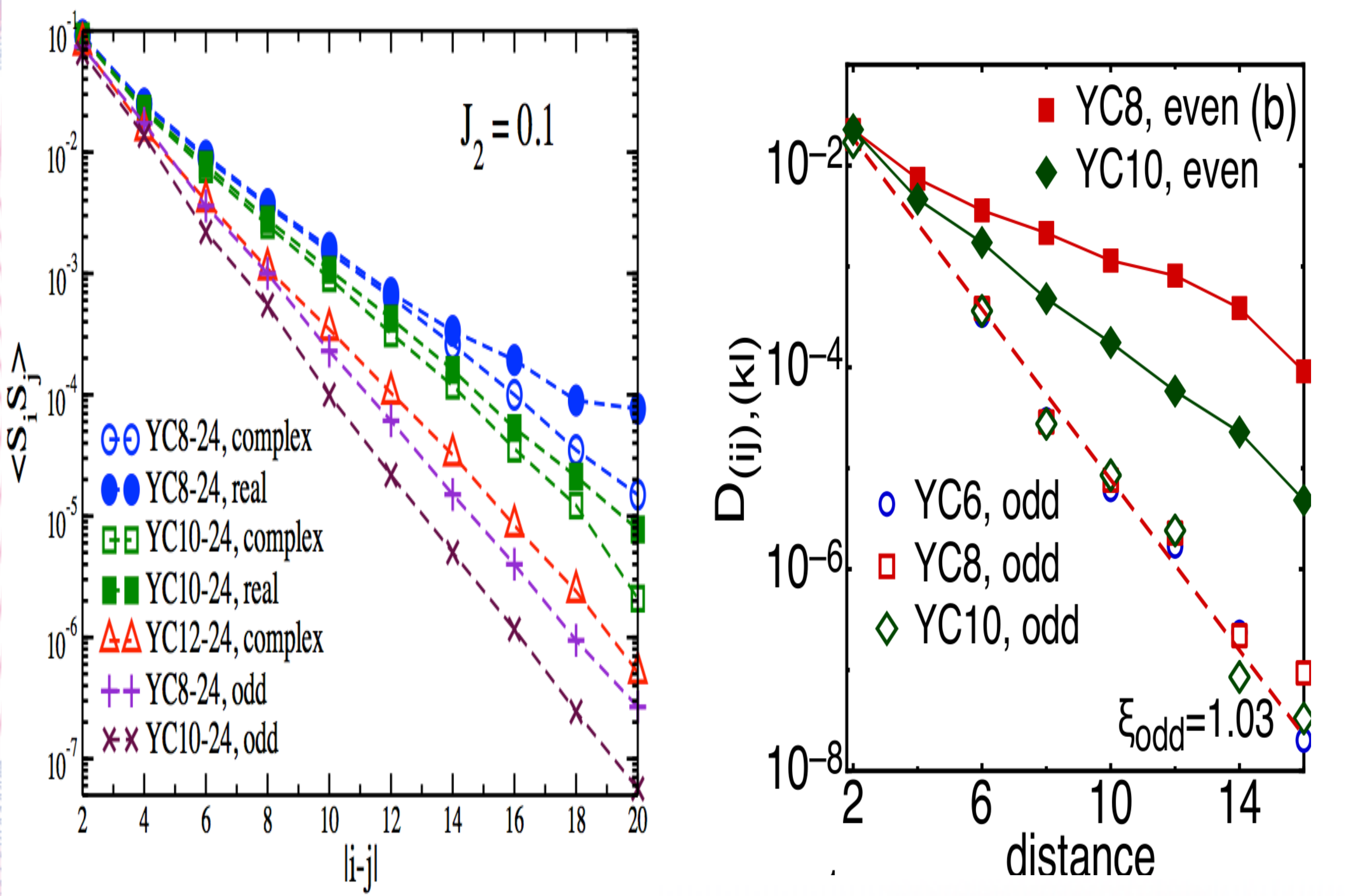


SL phase around J2=0.1, odd sector, the nematic order is strong

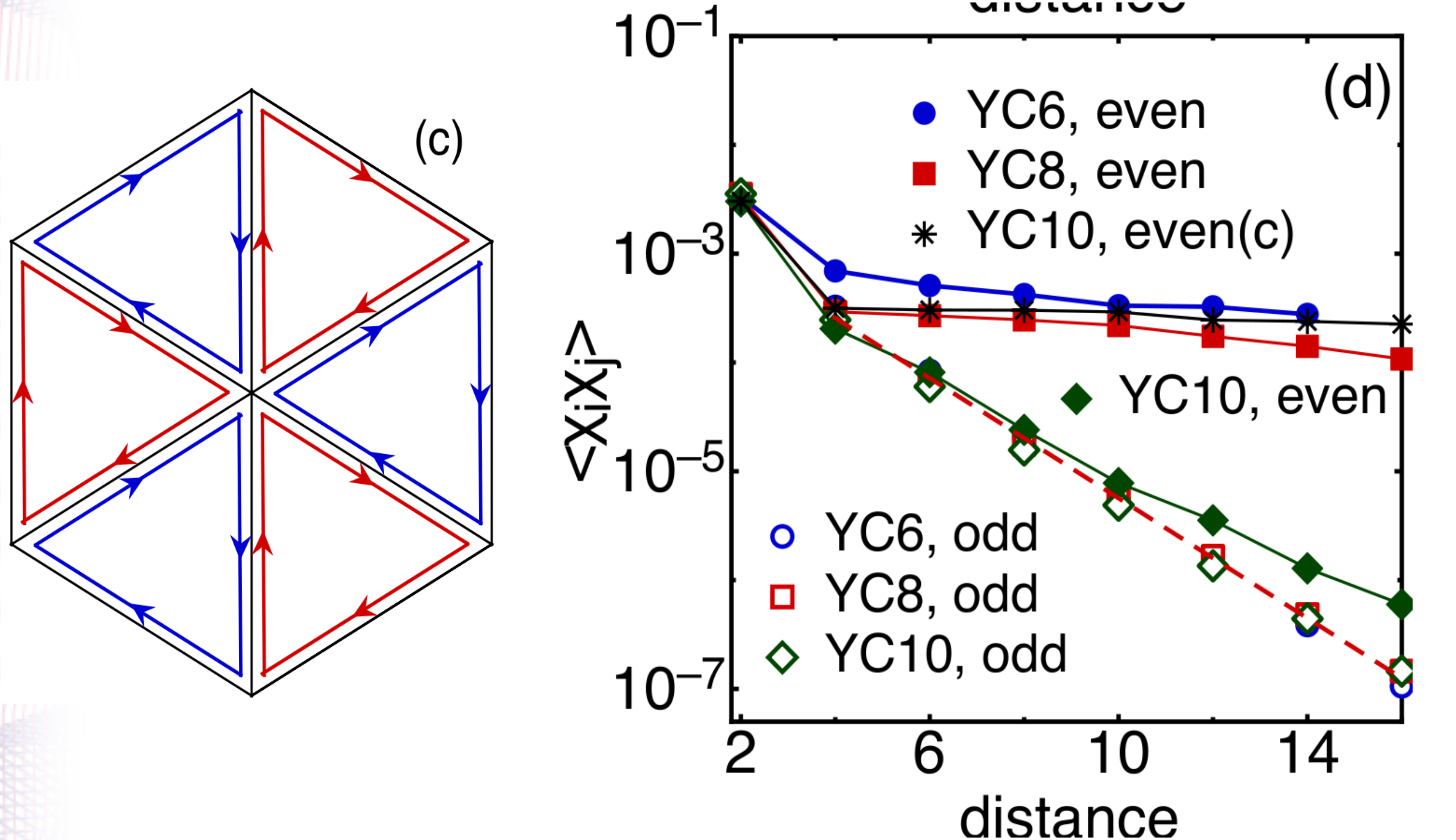
(c) J_2=0.1, YC10-24, odd sector



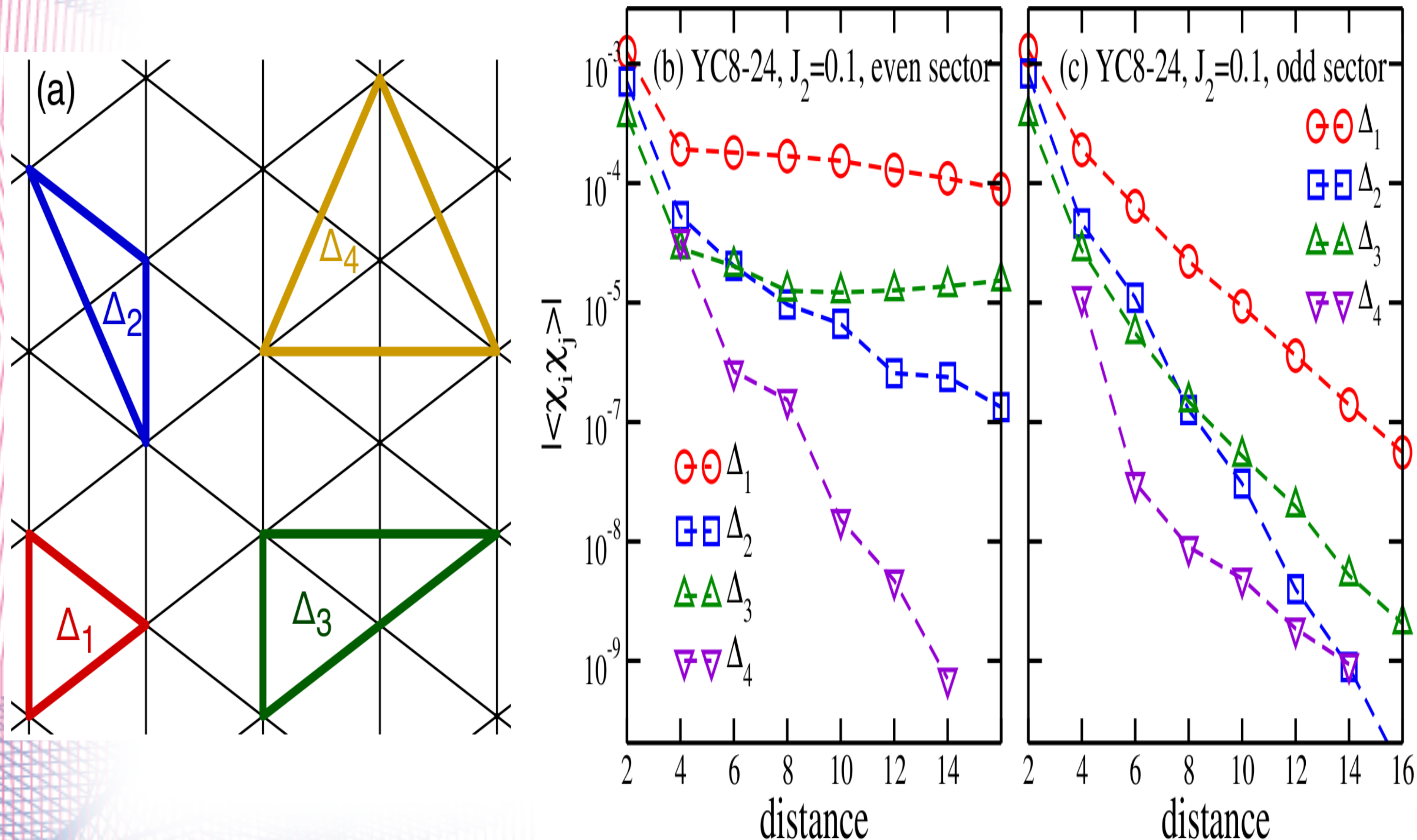
SL phase around J2=0.1, spin and dimer exponential decay



Long range chiral-chiral correlation is robust in even sector

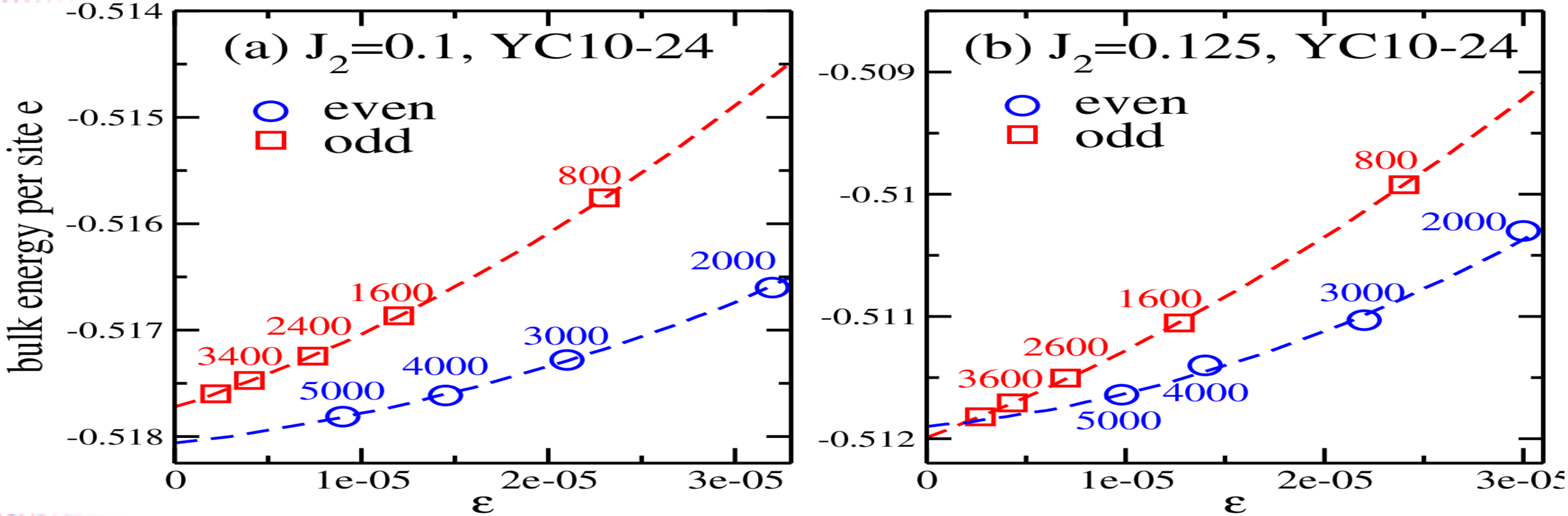


Comparing of the chiral correlations in two sectors



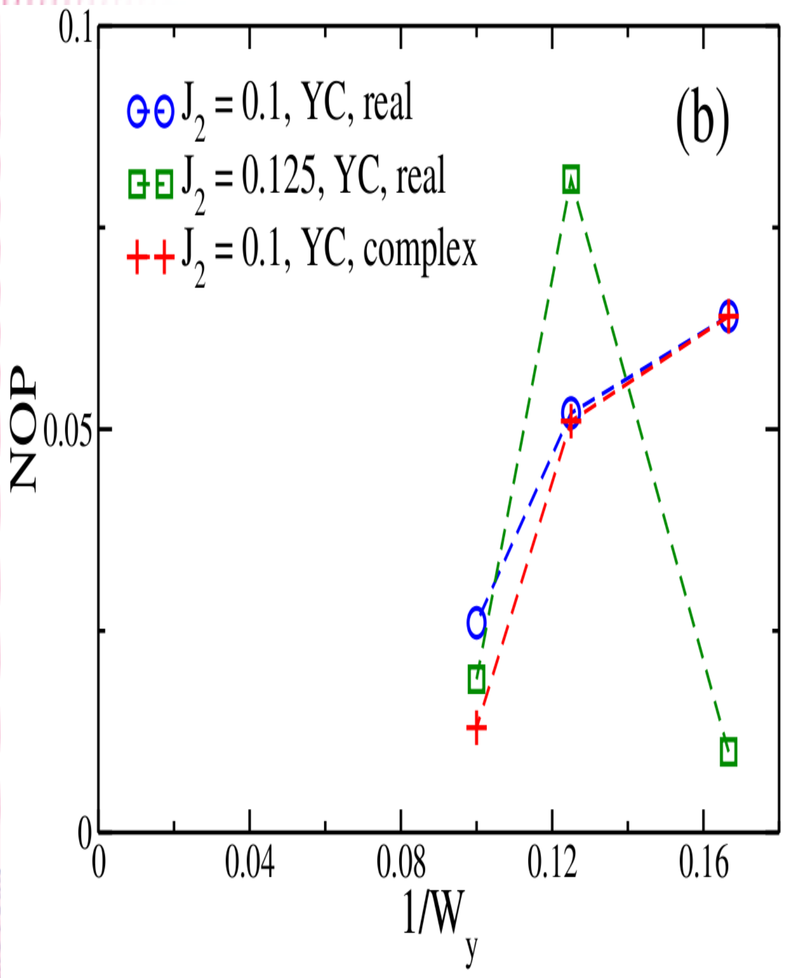
SL phase, near degeneracy, spin and singlet gaps

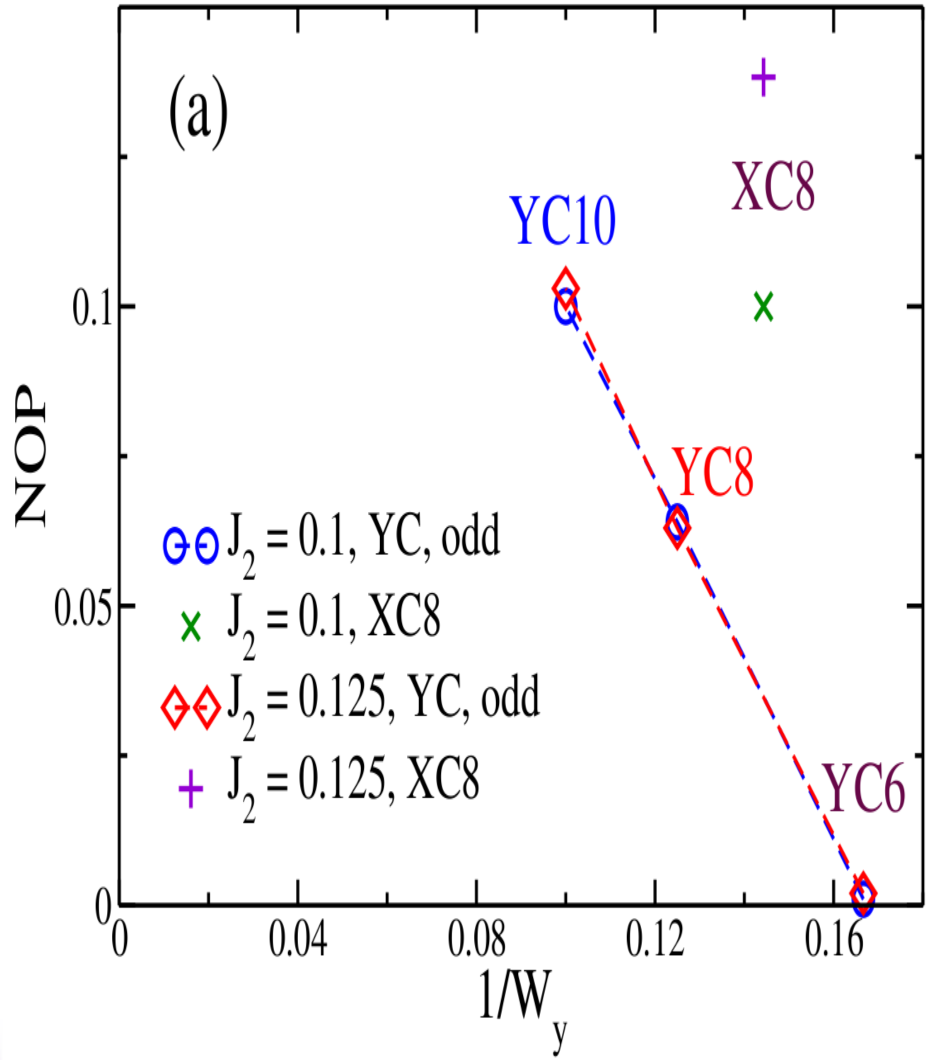
J_2,YCL_y	$e_{\rm even}$	$e_{\rm odd}$	Δe	$\Delta_{\rm T}$	$\Delta_{\rm S}$
0.1,YC6	-0.5155	-0.5210	0.0055	0.365	0.30
0.1,YC8	-0.5171	-0.5195	0.0024	0.335	0.26
0.1,YC10	$-0.5181(2)$	-0.5177	$-0.0004(2)$	0.30(1)	0.18
0.125,YC6	-0.5104	-0.5145	0.0041	0.389	0.33
0.125,YC8	-0.5115	-0.5133	0.0018	0.343	0.22
0.125,YC10	$-0.5119(2)$	-0.5120	0.0001(2)	0.30(1)	0.15



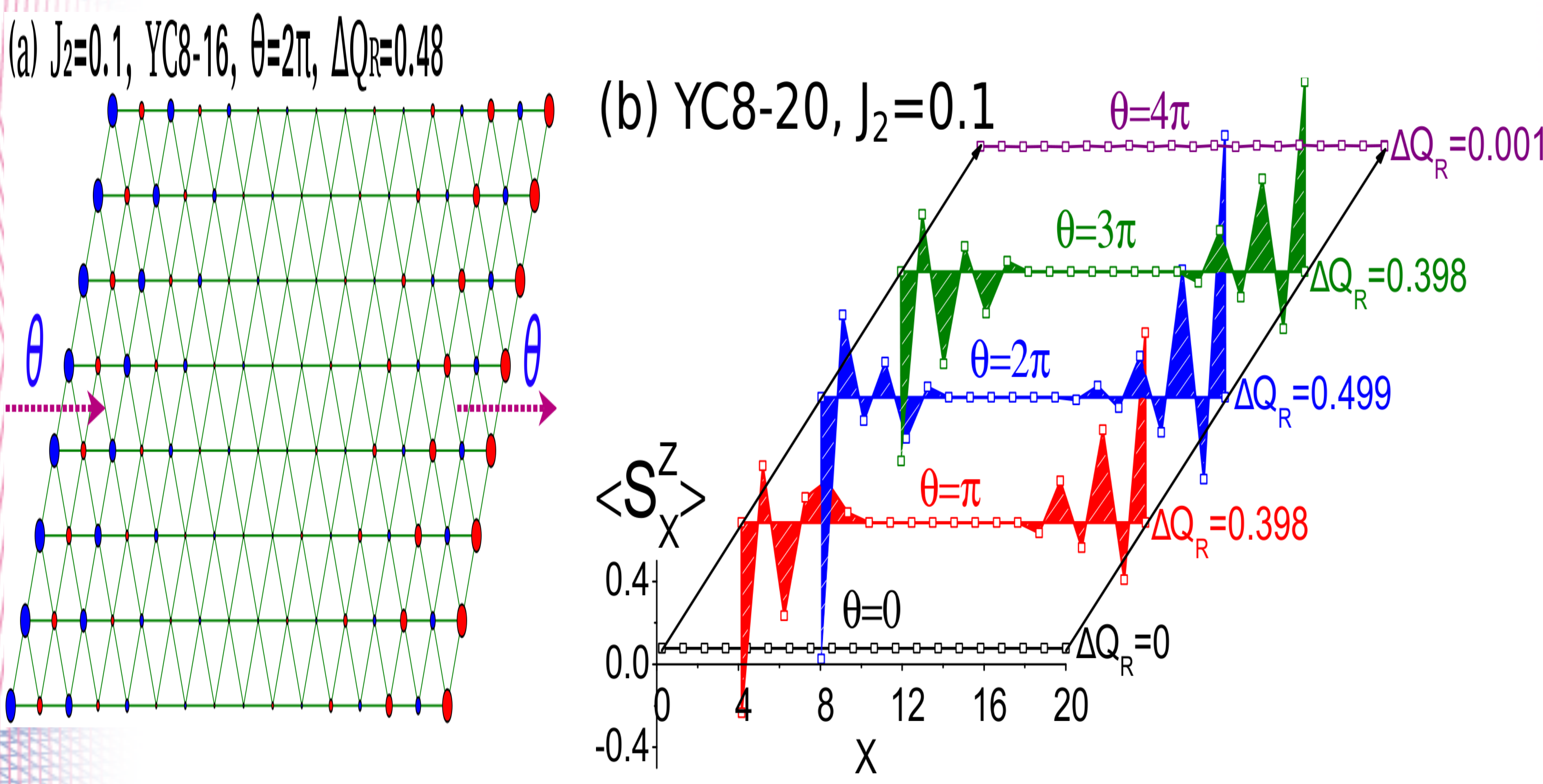
The transfer matrix longest correlation length is about 1

Anisotropy is stronger in spinon sector

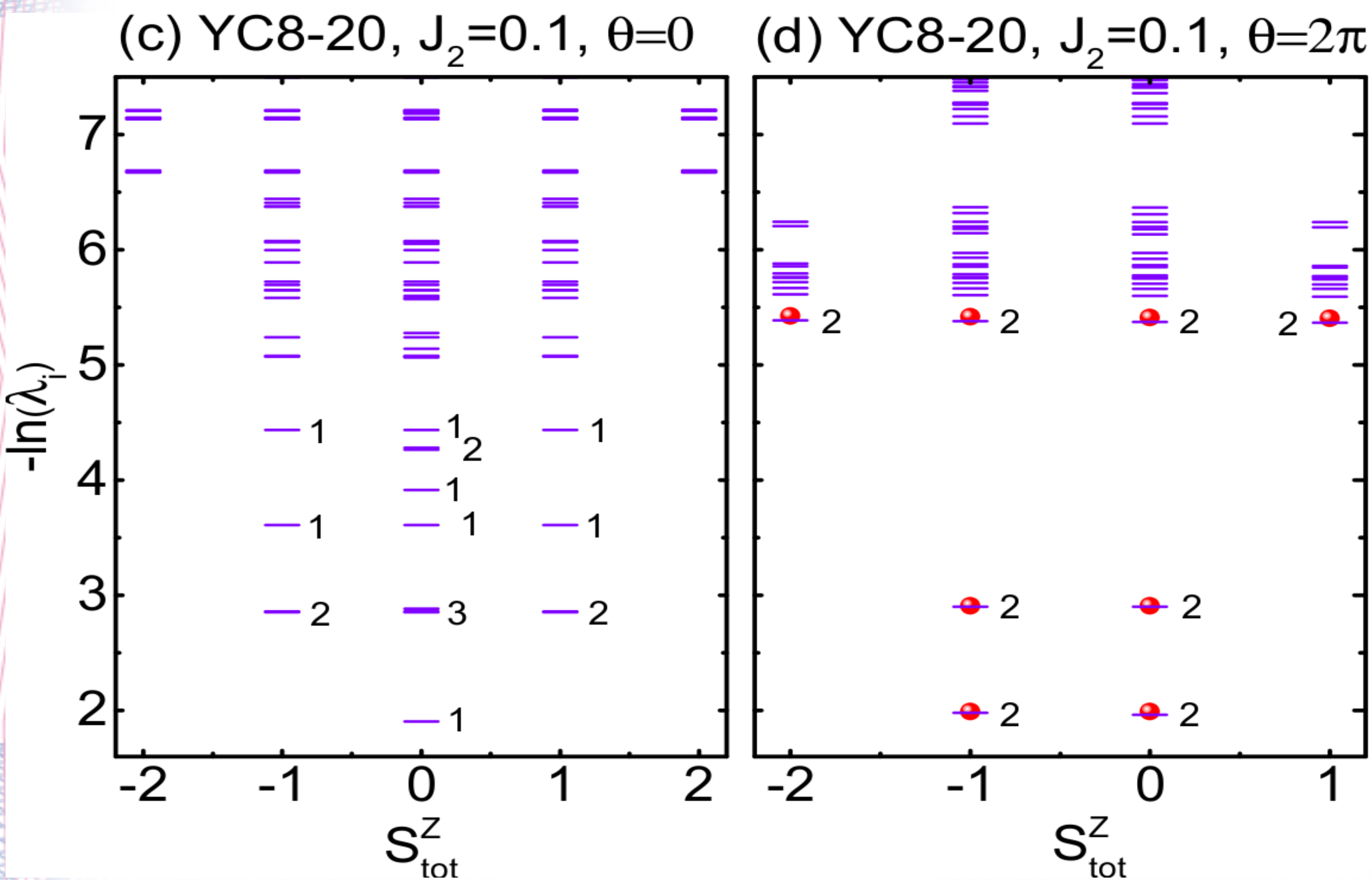




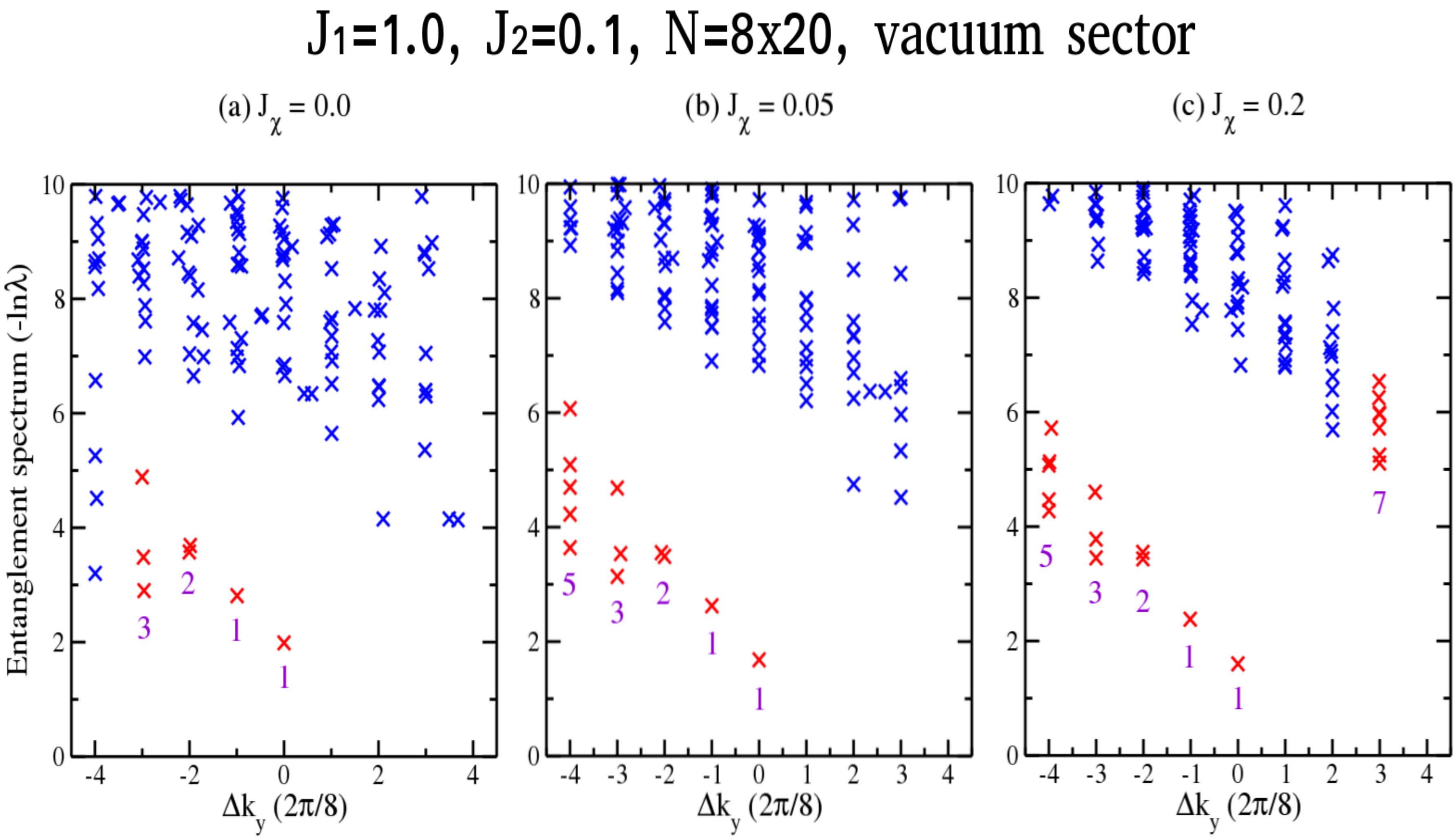
SL phase around J2=0.1, inserting flux 2pi gives fermionic spinon sector



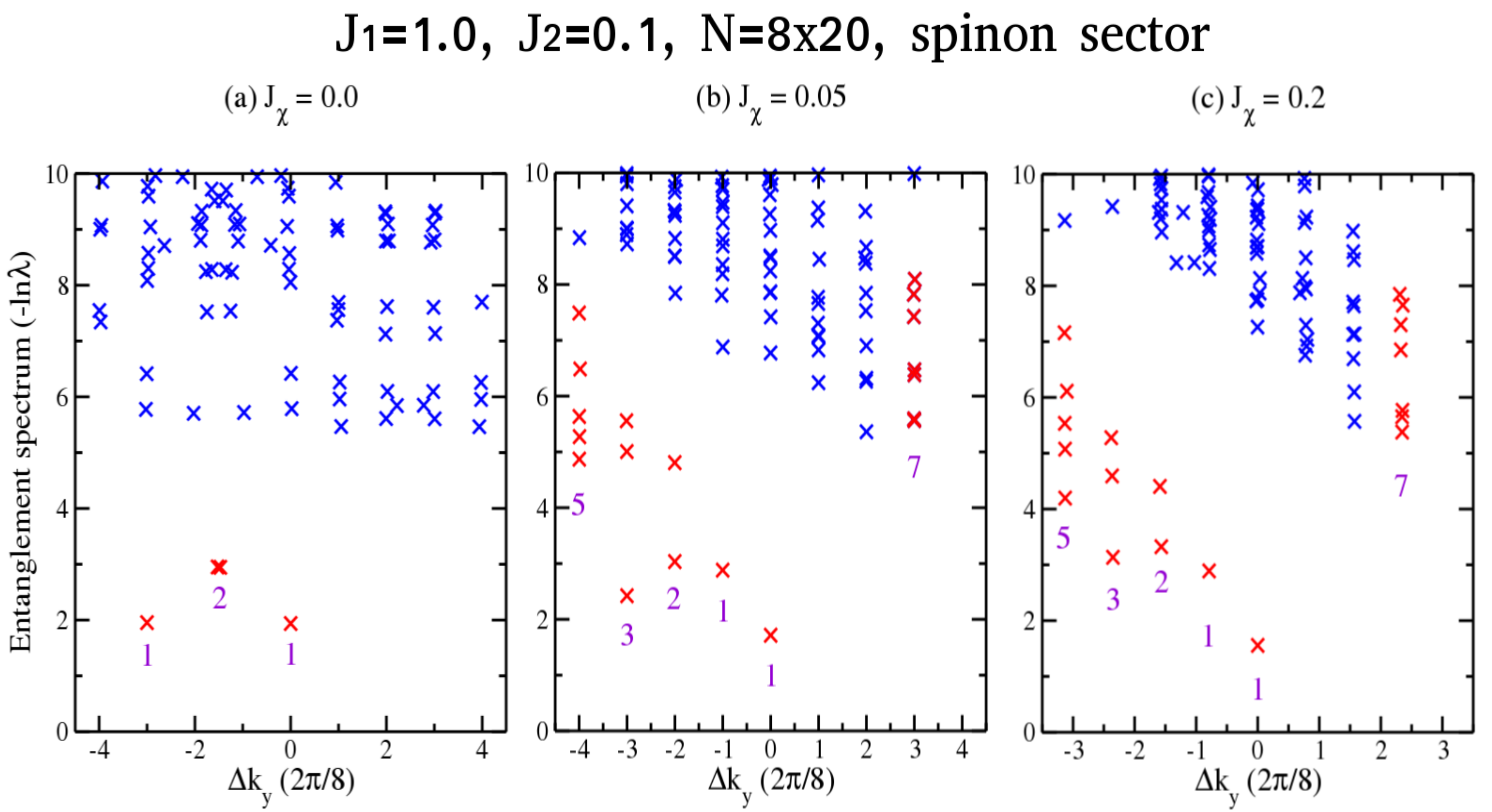
spectrum of the vacuum and spinon sectors



Entanglement spectrum of the vacuum sector and additional Jx (S1xS2)*S3



Entanglement spectrum of the spinon sector and additional Jx (S1xS2)*S3



Fermionic spinon sector at Jx=0 ?

Y. Qi & L. Fu, Phys. Rev. B; M. Zaletel, Y.-M. Lu, & A. Vishwanath (2015))

Competing Chiral Spin Liquid and Z2 Spin Lqiuid on Triangular Spin-1/2 J1-J2 Model

Two topological sectors, their bulk energies are near degenerating.

The CSL is identified in the vacuum sector; TRS is spontaneously breaking; it connects to a robust CSL by adding three spin chiral vector terms (Jx– 0.02).

The fermionic spinon sector for Z2 spin liquid is identified in the spinon sector---no TRS breaking with characteristic ES for Z2 (sign for symmetry fractionalization?).

Jx=0.02 to 0.05 will induce a quantum phase transition in the spinon sector so that the whole system becomes CSL.

Thank you